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A Correlated Pulse Generator for Thermal Neutron Coincidence and Multiplicity Counting Applications

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Abstract

A correlated pulse generator has been developed for use with thermal neutron coincidence and multiplicity counting systems. The pulser can produce arbitrary singles, doubles, and triples rates up to total count rates of ~200 kHz. The pulser presently is implemented as a plug-in card for industry-standard personal computers. The user interface allows the user to control the pulser by specifying either (1) pulser rates, (2) measured rates with shift register coincidence circuits, or (3) simulated plutonium sample parameters. The pulser is intended to assist with shift register testing, electronic circuit development, algorithm and software development, software testing, refresher training in neutron coincidence counting, and for demonstrations of neutron coincidence counting. The pulser can also be operated as a digital pattern generator producing programmed sequences such as periodic pulses or bursts. Six pulsers have been fabricated and are ready for use.

Introduction

A correlated pulse generator has been developed to simulate neutron pulses from thermal neutron coincidence counters. The purpose is to provide a convenient and flexible source of simulated neutron pulses for measurement control, quality control, diagnostics, and training for neutron coincidence counting systems, for neutron coincidence and multiplicity counting hardware and software development and testing, and for general neutron coincidence and multiplicity counting research and development. An earlier pulse generator [1] has also been developed for testing coincidence electronics.

In thermal neutron coincidence counting, the measured quantities are the singles and doubles rates — also called the totals and reals rates. The singles rate is just the total neutron count rate and the doubles rate is the measured rate of correlated pulse pairs in the neutron pulse stream. In thermal neutron multiplicity counting, the measured quantities are the singles, doubles, and triples rates. The triples rate is the measured rate of correlated pulse triplets in the neutron pulse stream. Because the neutron lifetime is typically tens of microseconds in a thermal neutron counter, the correlated pulses are distributed over a long time period and are counted in coincidence gates that are tens of microseconds long. The neutron lifetime in a thermal neutron counter has approximately an exponential behavior, i.e., the probability p of a detected neutron surviving to time t is

$$p \cong \frac{1}{\tau} e^{-t/\tau},$$

where τ is called the neutron die-away time.

The correlated pulse generator is designed to produce arbitrary combinations of singles, doubles, and triples rates up to a total count rate of ~200 kHz. The correlated neutrons are distributed exponentially to simulate neutron behavior in a thermal neutron counter.

Technique

The pulse sequences are based on random numbers generated by a dual shift register random number generator developed by Swansen and Ensslin [2] and later implemented in a field programmable gate array (FPGA) [1]. The time t_s between singles events is calculated from the equation

$$t_s = -\frac{1}{S}\log_e(r),$$

where S is the singles rate and r is a random number between 0 and 1. Likewise, the times t_d and t_t between doubles and triples events, respectively, are

$$t_d = -\frac{1}{D}\log_e(r)$$

and

$$t_t = -\frac{1}{T}\log_e(r),$$

where D and T are the doubles and triples rates, respectively. Similarly, the time between a doubles or triples event and a following correlated pulse is

$$t_s = -\tau\log_e(r).$$

The pulser uses four memory banks to manage the pulse stream. Each bank has 16,384 bits and each bit corresponds to 0.5 µs. A set bit (1) corresponds to a pulse and a clear bit (0) corresponds to no pulse. One of the four banks is read out to the output circuit while a second bank is being filled. The pulser program calculates the time differences based on the equations above and fills the appropriate memory locations with "1"s as needed. A third bank is used to handle overflows from the bank being filled, e.g., the first pulse of a triples event can occur near the end of the bank, so that the second and third pulses likely fall beyond the end of the bank. After a bank has been read out to the output circuit, its contents are cleared and the bank functions are rotated so that the overflow bank is filled next and the filled bank becomes the output bank. There is no time lost as a result of the bank rotation; the output pulse stream is continuous. It is essential that the banks are filled faster than they are read out so that no gaps occur in the pulse sequence. The software checks the readout status after it fills a bank; if the readout of the previously filled bank is already finished, an error message is generated.

No pulses are lost as a result of overlaps. If a calculated pulse time corresponds to a bit that is already set, then the pulser software sets the first cleared bit it finds above the calculated position. This is very similar to the derandomizer circuit at the input of the shift register coincidence circuits used with thermal neutron coincidence counters; if the shift register bit is already set when another pulse arrives, the new pulse is saved in a buffer until a shift register bit becomes available.

Hardware

Presently, the pulser is a half-length E-ISA plug-in board for an industry-standard personal computer (PC). The four storage banks are implemented with a 64-Kbyte dual-port static random access memory (SRAM). An FPGA logic device provides the concurrent readout of the memory and serial pulse stream conversion.

After filling internal memory with a lookup table corresponding to the delta time for singles, doubles, and triples, the Pentium® processor begins the real-time task of loading the dual-port SRAM. The processor first reads a random number generator contained in the FPGA. This 14-bit value is then used as an index into the delta-time lookup table in internal memory. The scalar delta-time value is converted to a bit location in SRAM, the bit is set, and the process repeated until the bank is filled. Concurrently, the FPGA is following at least a bank behind the Pentium, reading each 16-bit word and converting it to a serial bit stream. The serial bit rate is 4 MHz so each bit is 250 ns wide. A pulse corresponds to a 0 bit followed by a 1 bit so the minimum pulse separation is 500 ns.

An optional "randomizer" may be selected for the output bit stream. This circuit is located in the FPGA and provides a random delay on the output pulses of up to 500 ns with a 31.25-ns resolution. Each 250-ns-wide pulse into the randomizer is reduced to a 15.625-ns pulse and delayed between 32 ns and 500 ns. The delay time is determined by the four least significant bits of a 20-bit random number generator. With the randomizer, pulse pair separation of down to 15.625 ns is possible.

Software

The pulser software is a small PC program written in C that runs under DOS (the PC disk operating system). The software was not written for Windows® because the PC microprocessor must spend full time storing pulses in the four data banks. The program should not be operated in a DOS window under Windows.

There are two main parts to the pulser program — the user interface and the pulse generation parts. The user interface gives the user a choice of three modes of operation.

In one mode of operation, the user specifies the desired pulser singles, doubles, and triples rates. Note that the pulser rates are much different from the rates measured by the coincidence circuits. The measured singles, doubles, and triples rate (S_m, D_m, T_m, respectively) are related to the pulser singles, doubles, and triples rates (S, D, T, respectively) as follows:

$$S_m = S + 2D + 3T\ ,$$

$$D_m = (D + 3T) f_d\ ,$$

and

$$T_m = T f_d^2\ ,$$

where the doubles gate fraction (f_d) is

$$f_d = e^{-P/\tau}(1 - e^{-G/\tau})\ ,$$

where P is the predelay and G is the gate length.

In the second mode of operation, the user specifies the desired measured singles, doubles, and triples rates. In this case the user must also specify the predelay and gate being used and the die-away time of the detector being simulated. The pulser software generates an error message if the requested rates cannot be simulated, for example, the rates $S_m = D_m =$ 0 and $T_m = 1000$ counts/s are not possible.

In the third mode of operation, the user specifies the parameters of the plutonium sample and the parameters of the detection system to be simulated. The detector parameters are the efficiency and die-away time, the electronics parameters are the predelay and gate, and the plutonium sample parameters are the effective ^{240}Pu mass, the neutron multiplication, and the alpha value; the alpha value is the ratio of neutrons from (α,n) reactions to the neutrons from spontaneous fissions.

Performance

If the pulser is operated with $S = T = 0$ and $D = 10000$ counts/s, then

$$D_m = D f_d = D e^{-P/\tau}(1 - e^{-G/\tau})\ ,$$

so the measured doubles rate should vary exponentially as a function of the predelay. To test the exponential behavior, a series of measurements was made with these pulser rates, a die-away time of 50 µs, a gate length of 64 µs and predelay values from 0 µs to 50 µs. The coincidence electronics package was an MSR4 [3] and the measurement software was the International Neutron Coincidence Counting (INCC) code [4]. The results are shown in Fig. 1, where the natural logarithm of the measured doubles rate is plotted vs the predelay. The straight line shown in the figure is a least-squares fit to the plotted points. The slope is -0.0202 ± 0.0002 (µs)$^{-1}$, which agrees with the expected slope of $-1/50 = -0.02$ (µs)$^{-1}$. The $P = 0$ intercept is 8.884 ± 0.006, which agrees with the expected value:

$$\log_e(D_m) = \log_e[D(1-e^{-G/\tau})] = \log_e[10000(1-e^{-64/50})] = 8.885\,.$$

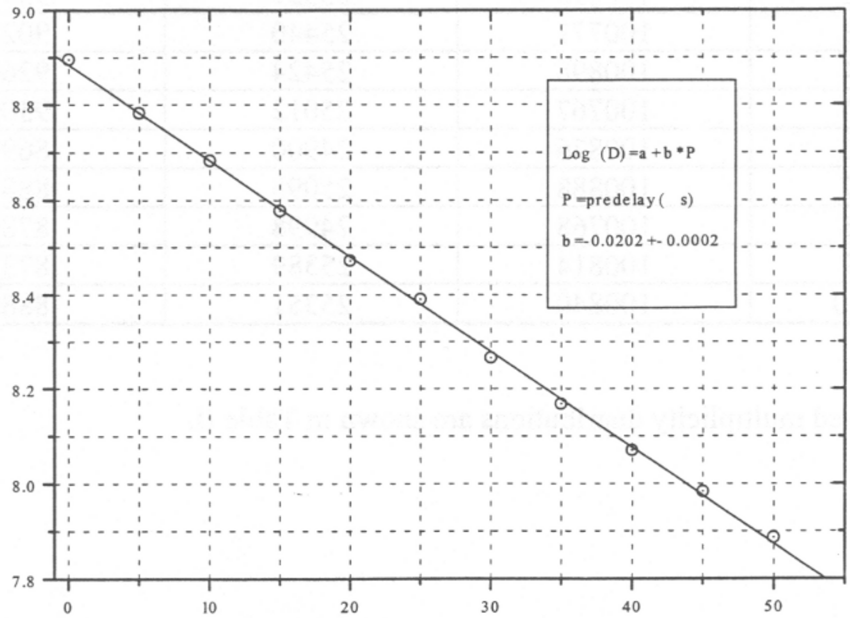

Fig. 1. Plot of the natural logarithm of the doubles rate vs the predelay for a die-away time of 50 μs and a gate length of 64 μs. The error bars (± 1 standard deviation) of the measured doubles rates are approximately the size of the plotted points.

The pulser was used to simulate a plutonium verification measurement using a thermal neutron multiplicity counter with an efficiency of 0.543 and a die-away time of 50 μs. The predelay was set to 3 μs and the gate length was set to 64 μs. The sample was 1416 g of plutonium (94% ^{239}Pu and 6% ^{240}Pu), the neutron multiplication was 1.092, and the alpha value was 0.962. The measurement time was 1000 s (10 cycles of 100 s each). The singles, doubles, and triples rates for the complete measurement were

S = 100836 ± 13 1/s,

D = 25250 ± 55 1/s,

and

T = 8982 ± 93 1/s.

The rates for each of the ten cycles are shown in Table I.

Table I. Singles, Doubles, and Triples Rates for 10 Measurement Cycles.

Cycle	Singles Rate	Doubles Rate	Triples Rate
1	100849	25527	8912
2	100895	25357	9337
3	100771	25440	9028
4	100898	25424	9260
5	100767	25012	9309
6	100876	24900	8692
7	100888	25098	8881
8	100768	24998	8786
9	100814	25389	8733
10	100840	25351	8888

The measured multiplicity distributions are shown in Table II.

Table II. Measured Multiplicity Distributions.

Multiplicity	Real-Plus-Accidental Counts	Accidental Counts
0	286724	347164
1	1505905	1780714
2	4068955	4666652
3	7582856	8447251
4	10994709	11858490
5	13255229	13868006
6	13850894	14044377
7	12873878	12675389
8	10885253	10408890
9	8486734	7891617
10	6172637	5581763
11	4220509	3719407
12	2738942	2352595
13	1693174	1419894
14	1001363	819476
15	571460	457570
16	313888	245637
17	165957	128277
18	85591	64409
19	42889	31322
20	20804	15006
21	9757	7024
22	4698	3165
23	2141	1436
24	974	624
25	461	311
26	214	139
27	65	50
28	35	13
29	12	9
30	4	9
31	6	4
32	2	1

The assay results are compared with the declared values in Table III. All values agree within statistical errors.

Table III. Comparison of Declared and Assay Values.

Quantity	Declared Value	Assay Value
Neutron Multiplication	1.092	1.093 ± 0.002
Alpha	0.962	0.983 ± 0.018
Plutonium Mass (g)	1416	1400 ± 15

The following experiment was done to compare statistical errors of the singles, doubles, and triples rates obtained from the measurement of a neutron source with those obtained from the pulser. First, a ^{252}Cf neutron source was measured in a thermal neutron counter for 1000 1-s cycles with $P = 3$ and $G = 64$. The pulser was then set to produce the same count rates using the known detector parameter τ. Another measurement of 1000 1-s cycles was made with the pulser. In both cases, the INCC code was set to calculate the sample standard deviations, rather than the theoretical ones. The results are shown in Table IV.

Table IV. Error Comparison for a ^{252}Cf Source and the Pulser.

	% Error (1 Standard Deviation)	
	^{252}Cf	Pulser
Singles rate	0.034 ± 0.001	0.035 ± 0.001
Doubles rate	0.145 ± 0.003	0.150 ± 0.003
Triples rate	0.763 ± 0.017	0.826 ± 0.019

The ^{252}Cf and pulser errors agree within three standard deviations for all the rates, but the pulser error for the triples rate is probably higher than that for ^{252}Cf. Exact agreement is not expected because the pulser does not produce the actual source multiplicity distribution, which for ^{252}Cf has multiplicities up to eight.

For typical gate lengths and die-away times for thermal neutron coincidence counters, the accuracy of the pulser rates is typically < 0.1% for singles, < 0.5% for doubles, and < 1.0% for triples. Because the minimum pulse separation of the output pulses from the pulser is 0.5 μs, the exponential die-away curve of the detector is approximated in 0.5-μs steps. The approximation is good for $\tau \gg 0.5$ μs, but gets rapidly worse as τ approaches 0.5 μs. Figure 2 shows the ratio of the measured doubles rate to the theoretical doubles rate as a function of die-away time. The theoretical doubles rate is that expected for a pure exponential die-away curve. The results shown in Fig. 2 are for doubles rates measured with $P = 1$ and $G = \tau$; the errors are approximately the size of the plotted points.

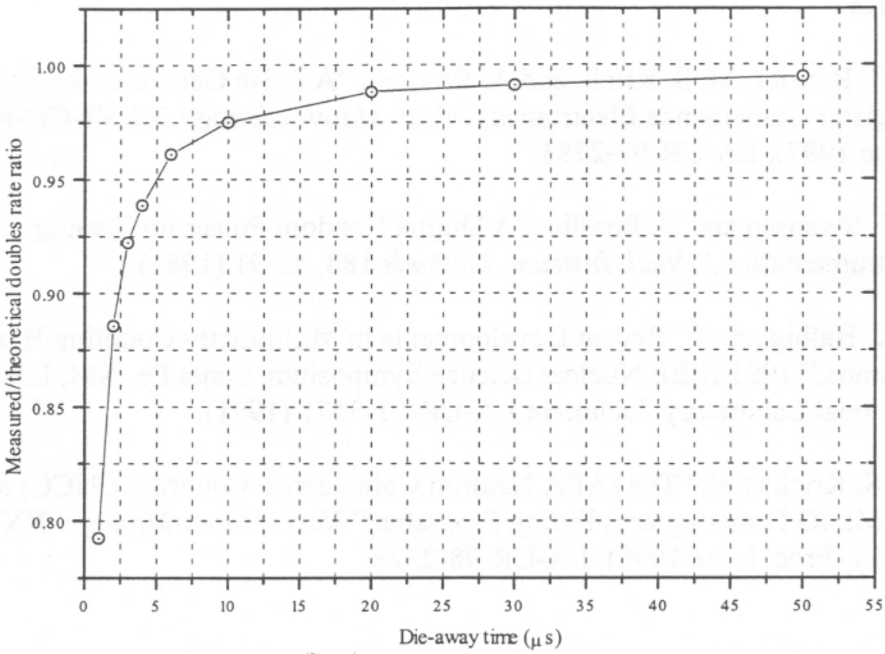

Fig. 2. Plot of the ratio of the measured doubles rate to the theoretical doubles rate vs the die-away time. The theoretical rates are calculated for a pure exponential die-away curve. The predelay is 1 μs and the gate length is equal to the die-away time. The standard deviations of the data points are approximately the size of the plotted points.

Concluding comments

The correlated pulser is ready for routine use. Six pulser boards have been fabricated. The ~200 kHz count rate limit is determined both by access to the pulser bank memory on the PC bus and by the PC processing speed. A 1-MHz correlated pulser should be possible using a pulser board that contains the pulser computational Digital Signal Processor (DSP) and fast memory; in that case, the minimum pulse separation should be reduced from 0.5 μs to 0.1 μs or less. There are two advantages to such a board besides the higher maximum output pulse rate. First, the pulser operation could be independent of the PC processor, so that any operating system could be used. Second, the pulser could be manufactured as a separate unit, with the PC simply supplying parameters and commands; the pulser, or a simplified custom version of it, could also be included with the shift register coincidence counting electronics for automated testing or other uses.

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